

Numerical Study on the Cavity-Induced Piping Failure of Embankment

H. J. Kim, G. C. Park, K. C. Kim, J. H. Shin

Abstract—Cavities are frequently found beneath conduits on pile foundations in old embankments. Cavity reduces seepage length significantly and consequently causes piping failure of embankments. Case studies of embankment failures indicate that the relative settlement between ground and pile supported-concrete conduit was the main reason of the cavity. In this paper, an attempt to simulate the cavity-induced piping failure mechanism was made using finite element numerical method. Piping potential is examined by carrying out parametric study for influencing factors such as cavity length, water level, and flow conditions. The concentration of hydraulic gradient adjacent to cavity was found. It is found that the hydraulic gradient close to the cavity exceeds considerably the critical hydraulic gradient causing piping. Piping failure potential due to the existence of cavity is evaluated and contour map for the potential risk of an embankment for piping failure is proposed.

Keywords—Cavity, Embankment, Hydraulic gradient, Piping.

I. INTRODUCTION

RECENTLY, natural disasters frequently occur around the world due to climate change. It causes flooding of rivers, collapse of embankments, and loss of roads. During flood season, drainage pumps operate to exclude storm water to rivers. In this case, cavity can be formed beneath conduit by the vibration from pump stations. Formation of cavity can cause a significant effect on the stability of embankment by shortening the length of seepage from riverside to inland [1]. Reduction of seepage length causes increase of hydraulic gradient, which increases the potential of piping and eventually causes embankment failure even at the lower water level than the design flood water level. In this study, influence of cavity on the embankment failure is investigated through numerical analysis.

II. CAVITY-INDUCED PIPING MECHANISM

Piping is a phenomenon which is caused by the loss of ground by scouring of soil particles. Precipitation incurs the difference of water level between riverside and inland. Seepage from riverside to inland is formed, and leakage around the toe of embankment occurs. When the seepage force exceeds the effective stress of the ground, then, the boiling of particles is started and scouring accompanying the piping channel is followed [2].

Piping can be found both in the embankment and beneath the foundation. There are several sources of piping failure in the embankment. Lack of cross section, omissions of filter layer,

defects of compaction, permeable layer under the structure and flow layer from poor contact between ground and structure can be factors to generate piping [3].



Fig. 1 Example of embankment failure by piping

When pump station is in operation to exclude storm water into the river, vibration can cause considerable dynamic effects on conduits and embankment body. The vibration can induce separation between conduit and foundation ground. The gap develops cavity beneath the conduit. Fig. 1 shows an example of failure beneath conduit triggered by piping through the cavity. Insufficient contact at ground-structure interface became a main flow route and eventually caused the failure. In this situation, the cavity shortened seepage length, thus critical hydraulic gradient was exceeded and failure was occurred.

III. MODELING CONSIDERATIONS

A. Introduction

Numerical model including cavity is considered. Two types of flow conditions were considered; steady state and transient. In case of steady state flow, the constant hydraulic boundary condition is applied. Meanwhile, in case of transient flow, the time varying hydraulic boundary condition is described. It is assumed that the width of conduit is sufficiently wide, and 2-dimensional model is used.

B. Modeling of Inflow

The seepage occurs through the void due to the difference of water head. The void is an important factor that determines permeability of ground. The continuity equation of flow, including transient conditions, in 2-dimensional model can be expressed as (1):

$$k_x \frac{\partial^2 h}{\partial x^2} + k_z \frac{\partial^2 h}{\partial z^2} = \frac{\partial \varepsilon_v}{\partial t} \quad (1)$$

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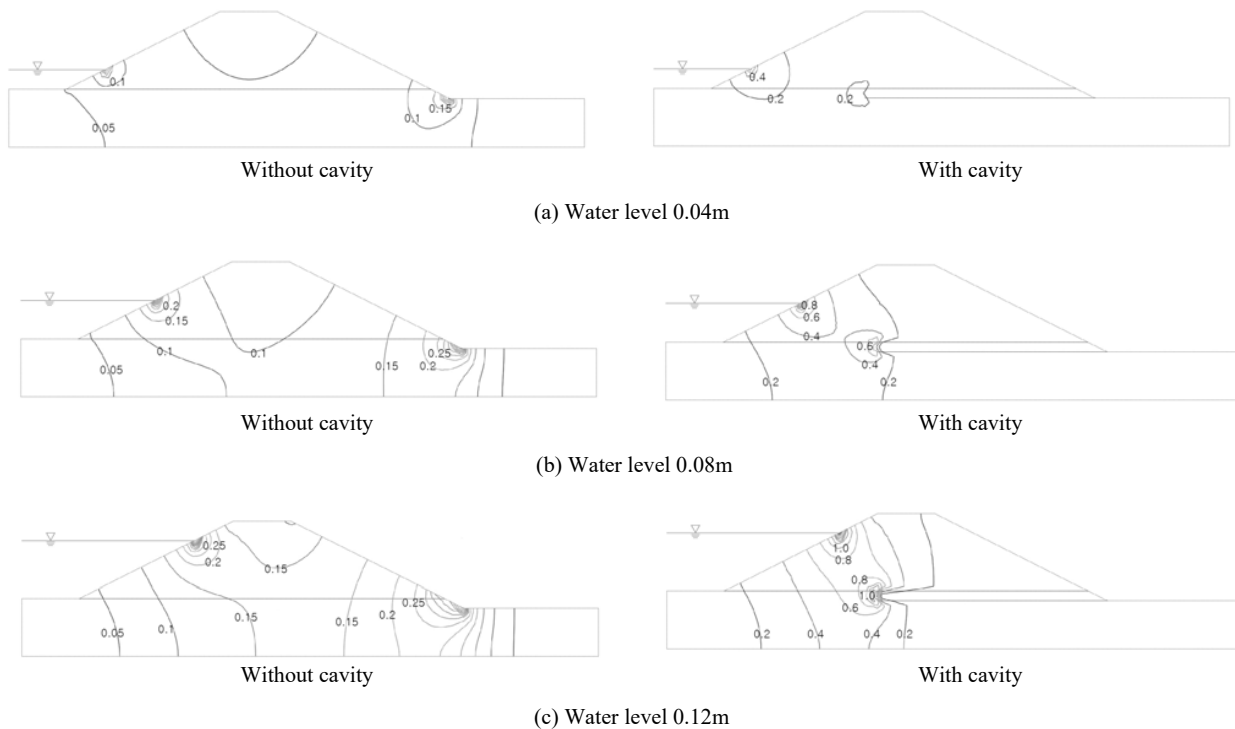


Fig. 4 Hydraulic gradient distribution of steady flow analysis

Fig. 5 shows the maximum hydraulic gradient for the water level of 0.12m. Without cavity, maximum hydraulic gradient of 0.66 was obtained at toe of embankment, meanwhile with cavity, 1.53 at the beginning point of the cavity.

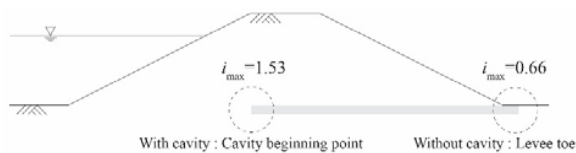
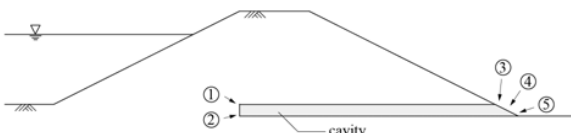
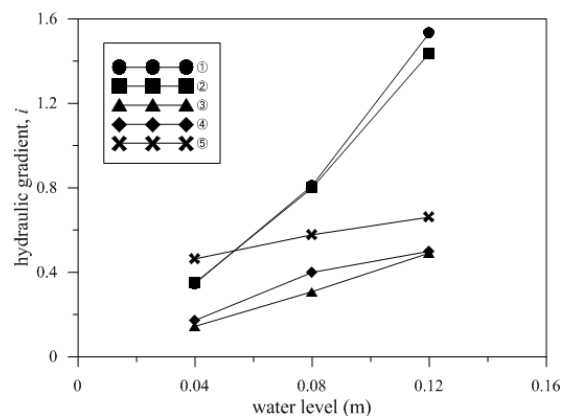


Fig. 5 Change of maximum hydraulic gradient

Fig. 6 shows the hydraulic gradient for different water level at the points where piping is potentially possible. The influence of cavity can be investigated by comparing the point ① and ③. At the beginning point of the cavity, the change of hydraulic gradient is very sharp. When the water level is higher than 0.12m, the hydraulic gradient exceeds critical value, thus it can be mentioned that the piping failure starts at the point.



(a) Points of piping consideration



(b) Hydraulic gradient curve

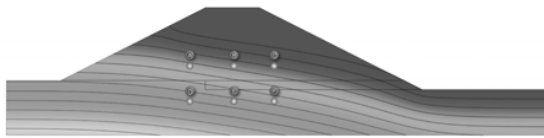
Fig. 6 Water level-hydraulic gradient curve of steady flow analysis

B. Transient Flow

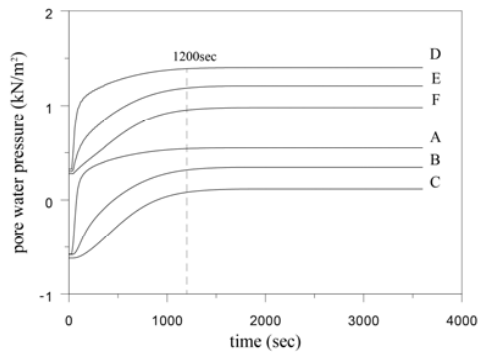
Hydraulic gradient varies with time in transient flow. Fig. 7 shows the pore pressure with time for each Case. The time required to reach steady state is different whether there is cavity or not. The time to reach hydraulic steady state was 1200sec without cavity and 600sec with cavity respectively.

Time dependence was investigated for the 6 points by carrying out analysis for the water head with water level 0.12m. This information is valuable in determining control time for the centrifuge model test.

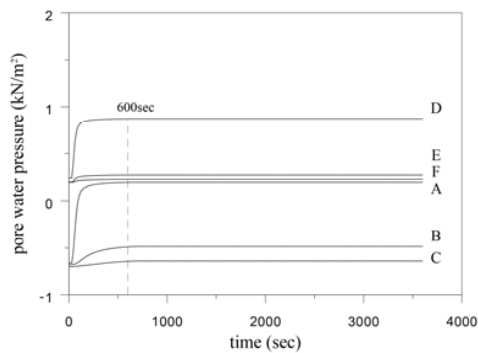
When there is cavity, the time to reach equilibrium state decreases significantly due to the reduced seepage length. Fig. 8 compares seepage lines for each case.



(a) Points of pore water pressure measurement



(b) Without cavity

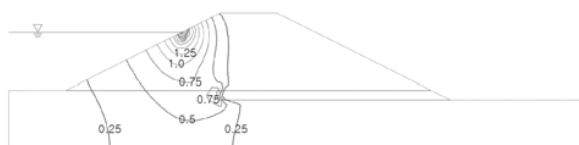


(c) With cavity

Fig. 7 Pore pressure development with time



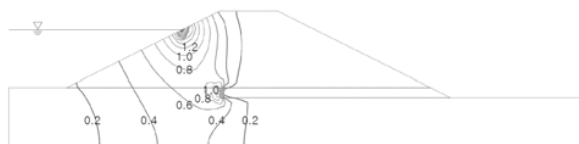
Without cavity



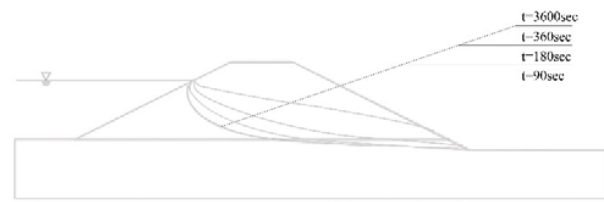
With cavity

(a) $t=90\text{sec}$

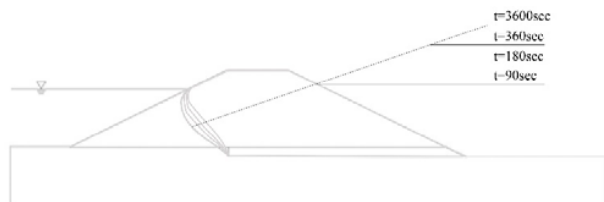

Without cavity



With cavity

(b) $t=180\text{sec}$


(a) Without cavity



(b) With cavity

Fig. 8 Seepage line

Fig. 9 compares the concentration of hydraulic gradient for transient flow. In case where cavity is developed, concentration of hydraulic gradient occurs at the beginning point of the cavity. The concentration of hydraulic gradient is getting intensive with time. Eventually the hydraulic gradient exceeds the critical gradient, and the piping failure starts.

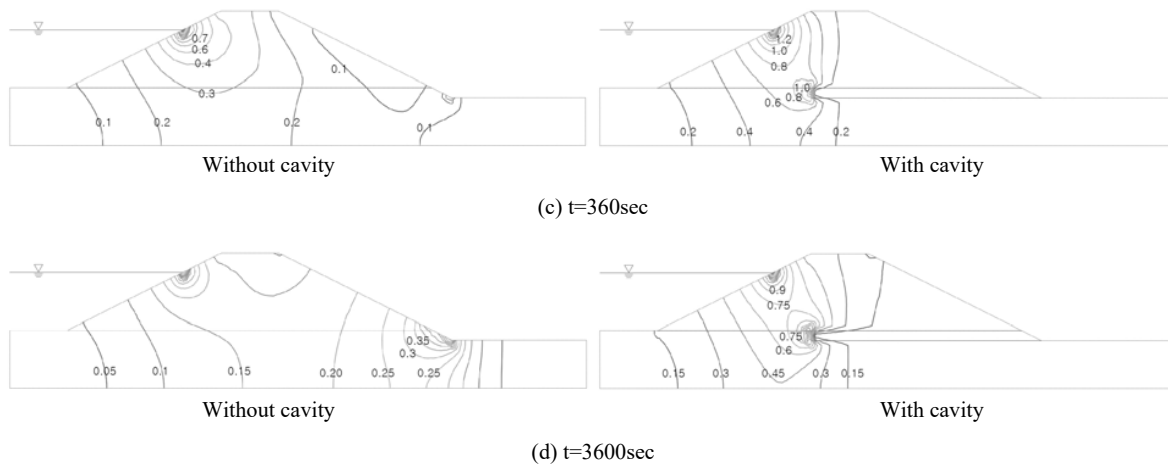


Fig. 9 Hydraulic gradient distribution of transient flow analysis

V. CONCLUSIONS

The piping development mechanism of embankment with cavity is investigated using the numerical modeling method. It is found that the effect of cavity on piping is crucial. Significant increase of hydraulic gradient was found at the beginning point of the cavity. The highest hydraulic gradient was occurred at embankment toe both for steady state and transient analysis in case without cavity, and it did not exceed the critical value. Meanwhile in case with cavity, the highest hydraulic gradient occurred at the beginning point of the cavity, and exceeds critical gradient of cavity and eventually leads to piping failure.

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REFERENCES

- [1] G. C. Park, "A study on piping failure of levee using centrifuge model test," Master Thesis (in Korean), 2014.
- [2] S.W. Jin, N.R. Kim, D.S. Kim, "Reproduction of piping failure due to the permeable layer using centrifuge test," *Journal of the Korean Society of Civil Engineers*, vol. 31, no. 1C, Jan. 2011, pp. 1-10.
- [3] J.M. Kim, B. H Choi, S.Y. Oh, K.M. Kim, "Numerical studies for the safety estimation of box-culvert in levee," *Journal of Korea Water Resources Association*, vol. 39, no.6 Jun. 2006, pp. 479-486.
- [4] D. G. Fredlund, A. Xing, "Equations for the soil-water characteristic curve," *Canadian Geotechnical Journal*, vol. 31, no. 3, pp. 521-532, 1994.
- [5] K. H. Kim, G. C. Park, D. R. Kim, J. H. Shin, "Evaluation of piping stability under dynamic conditions," in *Proc. 8th International Symposium on Underground Construction in Soft Ground*, Seoul, 2014, pp. 91-95.